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Rising grain prices in response to phased climatic change during 1736–1850 in the North China Plain

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Abstract Grain price volatility during historical periods is regarded as an important indicator of the impact of climate change on economic system, as well as a key link to adjust food security and social stability. The present study used the wheat prices in Baoding Prefecture, China, during 1736–1850 to explore connections between climatic transition and grain price anomalies in the North China Plain. The main findings were as follows: (1) The grain price change showed an apparent correspondence with climatic transition. The period 1781–1820 was a transition phase, with more extremes and decreased precipitations when the climate shifted from a warm phase to a cold one. Corresponding with the climatic transition, the grain price during 1781–1820 was characterized by that the mean of the original grain price series was significantly higher (lower) than the previous (later) phase, and the variance and anomaly amplitude of the detrended grain price series was the highest during 1736–1850. (2) The correspondence between grain price extremes and drought events occurred in phases. Five grain price extremes occurred following drought events during 1781–1810, while extreme droughts were the direct cause of the grain price spike during 1811–1820. (3) Social stability affected by climate change also played an important role in the grain price spike between 1811 and 1820. Paralleling the pathway of "precipitation-grain production-grain price", climate change could have an impact on grain price via the pathway of "precipitation-grain production-grain price-famine-uprising-grain price", as shown during the Tianli Uprising in 1813. These findings could contribute to an improved understanding of the interaction between climate change and human society during the historical period.

Keywords 18–19th century, Climate change, Grain price anomalies, North China Plain

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1. Introduction

Impacts of climate change on historical social development have been a great concern of research on global change (Büntgen et al., 2011; Butzer, 2012; IPCC, 2014; PAGES, 2014; Dong et al., 2017; Yue and Lee, 2018). Food security, as the foundation of economic and social stability, has long been regarded as a core issue for understanding the impacts of historical climate change (Bryson and Murray, 1977; Parry and Carter, 1985; Hsu, 1998; Fang et al., 2015; Slavin, 2016; Pei, 2017; Lee et al., 2017). As one of the factors regulating food security, the economic system's role is prominently reflected in the social system's response to the impact of climate change (Fang et al., 2014, 2017; Zhang et al., 2017). Grain price is an important indicator of the economic subsystem, reflecting the balance between grain supply and demand. It could be employed to measure food security and social stability risk induced by the imbalance between regional grain supply and demand that reflects the impact of climate change (Xiao, 2016). From this standpoint,

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regulation of grain supply and demand through price adjustment is actually, to a certain extent, an adaptive response of the economic subsystem to climate change (Fang et al., 2014, 2017).

Numerous studies have examined impact of climate change on grain price over the course of history. Many researchers have pointed out that climate change substantially impacted agriculture-based economies, as reflected in grain price. Bauernfeind and Woitek (1996, 1999) found that climate's impact on food prices intensified during a climatic deterioration period in Germany. They claimed that climatic factors, such as the growing season length for crops, were the most important determinants of grain price. Holopainen et al. (2012) found the temperature affected correlation between yields and prices of principle grains in Sweden in 1803–1914, and that the agriculture's susceptibility to climatic risks increased during the Little Ice Age. Pei et al. (2013, 2014) concluded that temperature substantially impacted the agrarian economy cycle in Europe during 1500–1800, and the long-term cooling led to abnormal price volatility and an agricultural economic crisis in the early 17th-century Europe.

Studies have also shown that the impact of climate change could be transmitted through price volatility to population crises. Appleby (1979) stated that the survival crisis in England and France during 1590–1740 could be closely related to food price volatility caused by climate change. The study asserted that more serious and frequent famines in France could be attributed to an outdated and monotonous agricultural planting structure. Galloway (1994) found that birth rate declines were closely related to increasing grain prices in Europe during 1460–1909, while mortality increases were associated with high grain prices, cold winters and hot summers. Scott et al. (1998) considered grain price an important negative feedback factor on cycles of birth rate, mortality, and migration in Penrith, England, in 1557–1812. Fraser (2011) claimed that social vulnerability in medieval Europe increased because of social development patterns highly dependent on trade and resources. Additionally, the impact of climate change led to grain price anomalies, famine, epidemics, wars and mass deaths in 14th-century Europe. Campbell and Gráda (2011) attributed three famines in England during 1300–1450 to continuous grain output reduction and soaring grain prices, probably caused by climate change.

The systematic grain price data of the Qing Dynasty in China, recorded with high spatiotemporal continuity and resolution, has attracted attention from researchers in the fields such as history, economics, and geography. Many studies have been conducted on: (1) grain price data collation and its reporting system, (2) the characteristics, social impacts and causes of grain price changes at national or regional scales, (3) the integration of grain prices and markets (Zhu, 2013).

There have also been considerable achievements made in research on the impact of climate change on grain price during the Qing Dynasty. Many studies have focused on the impact of extreme climatic events, such as droughts and floods, on grain prices during the Qing Dynasty. Wang and Huang (1999), Xie (2010) and Li (2016) suggested that short-term grain price peaks were significantly correlated with crop failures induced by severe drought and flood disasters in the lower reaches of the Yangtze River, Taiwan and Zhili Province. Li et al. (2008), Wang and Wang (2016), and Zhang (2014) claimed that grain prices during the Qing Dynasty had a certain correlation with natural disasters. Meanwhile they believed that social factors, such as population growth, grain storage and market, governmental food relief distribution, war, and currency, all also substantially impacted grain prices. Hao and Zhou (2008) proposed that the grain price in Shanxi Province during 1876–1879 were closely related to the process and spatial differences of the mega-drought. Shi et al. (2015) found that government regulation and food substitutes could, to some extent, constrain grain price increases caused by general drought. However, some controversy exists regarding the impact of long-term climate change on grain prices. For instance, Wang and Huang (1999), Xie (2010) and Li (2016) claimed that long-term climate change had no obvious impact on food prices because of governmental intervention, market supply, and other socioeconomic factors. Pei et al. (2016) noted that grain prices and gross domestic product per capita in China were closely related with temperature during 1600–1850, while the socioeconomic vulnerability to climate change increased because of population growth.

The North China Plain (NCP) housed the seat of the Qing Dynasty's political center. The social impacts of climate change in the NCP during the Qing Dynasty could provide representative cases for studying the mechanism of social impacts of climate change in historical China. From the end of the 18th century to the start of the 19th century, the social and economic impacts of climate change became increasingly prominent (Fang et al., 2013). Social instability increased because of climatic transition and increased drought and flood events. Based on the framework of food security, Fang et al. (2013) suggested that the agricultural production crisis resulting from climate change eventually triggered a social crisis. That study also explored the contribution of saturated land reclamation, weakened governmental disaster relief capacity, and improper quarantine policy to the formation of the crisis. As an important intermediate node, the grain price volatility during that process, and its role in the impact transmission need to be further discussed.

Based on annual grain price data and reconstructed series of climate change with high temporal resolution, this study quantitatively analyzed the impact of climate change on grain price volatility in the NCP during 1736–1850. This research is expected to improve the understanding of the interaction between climate change and human society during historical period.

2. Data and method

2.1 Study area

The NCP, as referred to in this study, includes most of Zhili (south to the Great Wall), northeastern Henan, and northwestern Shandong. This area roughly covers modern Beijing and Tianjin, most of Hebei, and part of Henan and Shandong (Fang et al., 2013). The NCP is an alluvial floodplain of the Haihe River and Yellow River, and surrounded by Yanshan Mountains to the north, Taihang Mountains to the west, and Shandong Hills to the southeast. Located in the northern warm temperate monsoon climate zone, the NCP frequently suffered from drought and flood disasters because of great inter-annual and seasonal precipitation variability (Li, 1990). During the Qing Dynasty, this area had dense population, developed agriculture, and similar socioeconomic conditions despite its wide expanse. The society and economy based on agricultural production were moderately sensitive to the impact of climate change, with certain adaptability (Fang et al., 2013). There was an integrated grain market in the NCP during the mid-Qing Dynasty (Hu, 2017), thus grain price acted both the roles of being impacted by climate change and adjusting the impact.

The main crops planted in the NCP during the Qing Dynasty were wheat, millet, sorghum, beans, corn and sweet potatoes. Wheat harvested in summer, and millet and sorghum harvested in autumn were the core and most valuable crops in the agricultural planting system of triple cropping every two years. The planting proportion of wheat amounted to 30–50%. Besides being a main food for the peasants' own consumption, the wheat planted in the NCP was primarily used as a commodity grain and accounted for a large proportion of the grain market during the Qing Dynasty because of the huge market demand (Li W Z, 1993; Li F B, 1993; Xu, 1999; Han, 2012, Li, 2016; Hu, 2017). The planting proportion of millet and sorghum was equivalent to that of wheat in the NCP during the mid-Qing Dynasty, but gradually decreased after the Reign of Jiaqing because of the widespread penetration of American cereal crops (Li F B, 1993). Millet and sorghum were mainly used for the peasants' own consumption. The market demand for millet and sorghum primarily originated from the farmers' selling wheat for income and buying coarse grains for subsistence. The commercialization rate and market position of the two were therefore relatively lower than those of wheat in the NCP (Li W Z, 1993; Xu, 1999; Han, 2012). Additionally, their price fluctuation pattern in the NCP during the Qing Dynasty resembled that of wheat (Huang, 2018).

The wheat price in Baoding Prefecture was selected as representative of the NCP's grain price. Baoding Prefecture, as the capital of Zhili Province during the Qing Dynasty, was located on the piedmont plain of Taihang Mountains. It was among the main winter wheat planting areas and adopts the agricultural planting system of triple cropping every two years (Han, 2012). The grain price in Baoding Prefecture during the Qing Dynasty had a varying pattern similar to those in Zhili Province and the Huai River basin (Zhu, 2014; Li, 2016). The wheat price in Baoding Prefecture had substantial co-integration relationships with more than 70% of the prefectures in Henan Province and Shandong Province (Hu, 2017). In the commodity trading network based on water transport in the NCP during the Qing Dynasty, Baoding was only a local commercial center. Its grain market was relatively small, with business extending from Tianjin and Beijing (Li, 2016; Xu, 2016). The grain price fluctuation in Baoding was therefore less affected by the grain input from outside. The linkage between climate and grain price in the NCP can be effectively reflected through the impact transmission process of "climate change-grain production-grain price volatility".

2.2 Grain price data sources and data processing

2.2.1 Data sources

Grain price data were obtained from two data sets. The first is the Qing Dynasty Grain Price Database, constructed by Wang at the Institute of Modern History of Taiwan Academia Sinica (http://mhdb.mh.sinica.edu.tw/foodprice). Another is the Grain Price Tables from 1821 to 1911 (Institute of Economics, Chinese Academy of Social Sciences, 2009). The two data sets were derived from the grain price lists in the imperial archives of the Qing Dynasty (Hu and Li, 2016). Both recorded the prices of various grains by month over time, and by prefecture as a statistical unit. The data in the Grain Price Tables are relatively complete, but cover only the reigns of five emperors during the Qing Dynasty (1821–1911). The Grain Price Database covers a longer period, from 1736 to 1910, but with missing data for some years (Luo, 2012).

For this study, the wheat price in Baoding Prefecture during 1736–1850 was selected to represent the grain price change in the region. Wheat price data during 1736–1820 were from the Grain Price Database. Data during 1821–1850 were from the Grain Price Tables, with the missing data to be supplemented by the Grain Price Database. The year 1736 is the first year of records in the Grain Price Database. Grain prices after 1850 were excluded to avoid the disruptive effect of the "currency crisis" from 1853 to 1859 and the decrease in silver prices after the 1870s (Peng, 2006; Yang, 2007).

2.2.2 Data processing from the grain price database

Baoding Prefecture's monthly wheat prices in the Grain Price Database were presented as maximum and minimum prices in the unit of "Cent/Dan" (Cent is an unit of silver money and Dan is an unit of weight in the Qing Dynasty) in subordinate counties in a given month. Because of regulatory changes for collating and reporting grain prices (Yu, 2014), wheat was considered "white wheat" (white skinned) and "red wheat" (red skinned) separately during 1736–1763, but only "wheat" during 1764–1910. Some data are missing among three kinds of wheat prices (Figure 1a, 1b).

Based on the characteristics of the prices in the Grain Price Database, the wheat price before February 1764 was calculated from the average prices of the "white wheat" and "red wheat". The unit of assembled wheat prices was then converted into "Taels/Dan" (Taels is a unit of silver money in the Qing Dynasty, 1 Taels=100 Cents) to match the Grain Price Tables data. Given that the data for "wheat" price in June 1751 and "white wheat" price and "red wheat" price during March–July 1768 were scattered and overlapped with other categories, they were suspected as copying errors and were discarded (Figure 1a, 1b).

The assembled wheat price data covered 124 years during 1736–1910, of which 83.9% had wheat prices for more than 6 months. These wheat prices were complete during the Reigns of Qianlong and Jiaqing (1736–1820), but incomplete after the Reign of Daoguang (Figure 1c).

2.2.3 Data processing from the Grain Price Tables

The wheat price data in Baoding Prefecture from the Grain Price Tables cover 1821–1911. The price unit is "Taels/Dan". They are presented in the lunar calendar month and year, the same as the original records.

To unify the grain price data for further analysis, the price data in lunar calendar were converted into Gregorian calendar format. The conversion employed the "Conversion system for the Gregorian calendar and lunar calendar in the past 2000 years" which is available on the Qing Dynasty Grain Price Database website. A Gregorian month may contain various days of 1–3 lunar months due to the difference between the two calendar systems. The monthly grain price in the Gregorian calendar was calculated from the average grain prices of the lunar months, weighted by the days of the lunar month contributing to the given Gregorian calendar month (Xie, 2008). The processed wheat price data in Baoding Prefecture covered most months and years during 1821–1911 (Figure 1d). The only exception was 1901, when social stability and the function of government were greatly affected by the invasion of eight Western nations and the Boxer Rebellion.

2.2.4 Integration of the two wheat price data sets

The two wheat price data sets in Baoding Prefecture were merged into one wheat price series covering 1736–1911, with the same price unit in Gregorian calendar years and months (Figure 1e).

Grain prices during the Qing Dynasty included maximum and minimum monthly prices of various grain types in subordinate counties of the given prefectures. The monthly wheat price was represented by the average of the maximum and minimum (Wang, 2003; Yu, 2014). The annual wheat price series during 1736–1850 was obtained by merging the two data sets and calculating the average monthly prices for each year. For 93.9% of the years with price data covering more than 6 months of the year, the annual price was directly calculated from the average of the monthly wheat prices of that year. For the 6 years with data coverage of 1–6 months, the annual price was given as the average of the revised monthly wheat prices (original wheat price/seasonal index). The seasonal index was represented by the ratio between the average price in the fixed month and the average of yearly wheat prices during 1736–1850, with a variation range of from 0.979–1.031 for the different months of a year.

There were no records on monthly wheat price for 1815. The annual price in 1815 was interpolated as the average of the annual wheat prices in 1814 and 1816 considering the following two facts. Firstly, the wheat prices in Baoding Prefecture during 1814 already began to decrease from August, which is in accordance with the falling grain prices of that year recorded in some local gazetteers in the region (Zhang, 2004). Secondly, there were no large-scale extreme drought events or other climatic anomalies in the NCP in 1815 (Zheng et al., 2005, 2018), while good grain harvests were recorded by many local gazetteers (Zhang, 2004).

2.2.5 Detrended wheat price series

Population, currency, and other socioeconomic factors affected the trend in the original wheat price series (Wang, 1992; Lu and Peng, 2005; Peng, 2006; Ge, 2011). Linear regression was employed to fit the trend of the wheat price. Abnormal values exceeding one standard deviation above the average wheat price were first excluded before linear fitting. The detrended wheat price series was obtained by subtracting the fitted trend from the original wheat price to eliminate disruption from long-term trends. The series was used to analyze the relationship between climate variation and grain price volatility.

2.3 Temperature and precipitation data

The reconstructed temperature series shows that, the historical temperature change was basically the same in North China and its sub-regions (Wang, 1990; Ge et al., 2002; Yan et al., 2012; Liu and Fang, 2017). The winter-half-year temperature series during the Qing Dynasty in North China was adopted for estimation of temperature change. The series

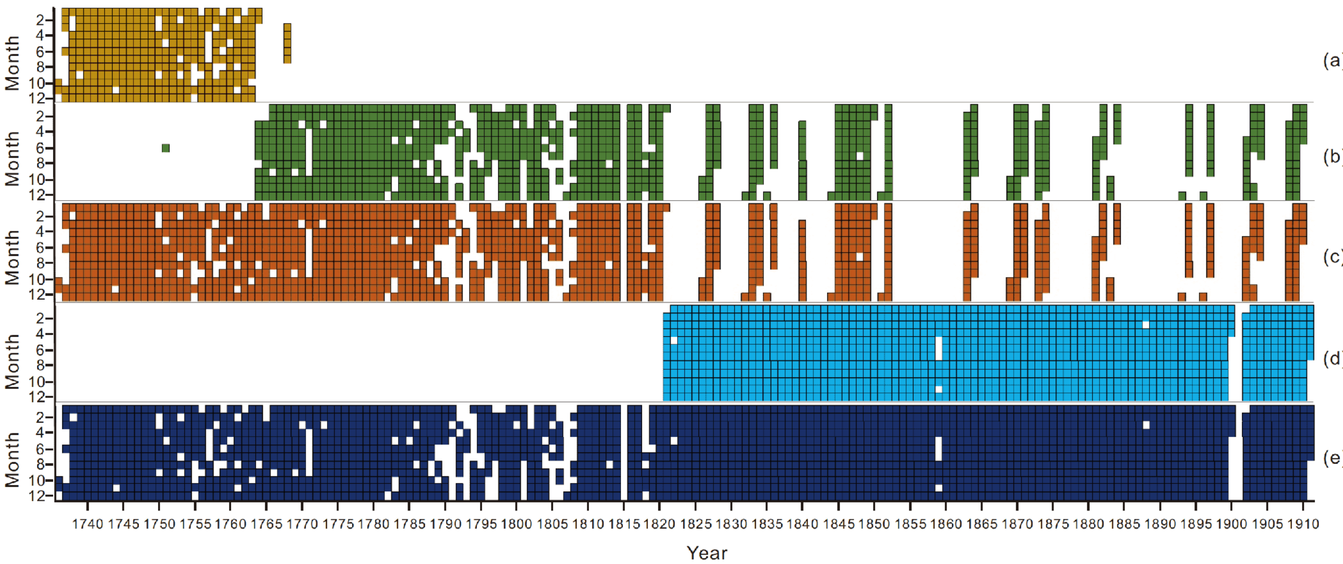

Figure 1 Temporal distribution of grain price data in Baoding Prefecture during the Qing Dynasty. (a) Prices of "white wheat" and "red wheat" from the Grain Price Database; (b) prices of "wheat" from the Grain Price Database; (c) assembled wheat prices from the Grain Price Database; (d) wheat prices from the Grain Price Tables; (e) merged wheat prices from the two price data sets.

was reconstructed in a 5-year resolution based on the records of anomalies in the first and last frost dates from the historical documents (Yan et al., 2012). The growing season of winter wheat in the NCP is generally from October to mid-June. The yield is sensitive to temperature in the seedling to jointing stages (late-October to mid-April). However, the influence of temperature in the heading to maturity stages (from late-April to mid-June) on the yield of winter wheat is uncertain (Xiao et al., 2014; Wu et al., 2018).

Considering the high correlation between the modern annual precipitations of Baoding and Shijiazhuang, Shijiazhuang's annual precipitation during the Qing Dynasty (1736–1911) was adopted. This was reconstructed based on the Yu-Xue-Fen-Cun records by Ge et al. (2005). The Yu-Xue-Fen-Cun records are a type of achieves in the Qing Dynasty, reported in memos to the Emperor documenting the precipitation information of either rain infiltration depth after rainfall or snow depth after snowfall. The records were converted into annual precipitation by employing soil physical models of rainfall infiltration and using an empirical regression relation (Ge et al., 2005). Precipitation change in most decades during the 18th and 19th centuries had similar features in the sub-regions of the middle and lower reaches of the Yellow River, such as those of Hebei, Jinnan and Weihe (Zheng et al., 2005). The precipitation series of Shijiazhuang could therefore reflect the decadal and annual precipitation variation in more broad area of the NCP.

2.4 Analysis of the relation between climatic transition and grain price variation

2.4.1 Phased climate change and grain price variation

The three phases of warm, transition, and cold were divided based on temperature differences during 1736–1850. The character of the transition phase in the NCP was analyzed by comparing the differences among the three phases in the averages, variations and other statistical indexes of temperature and precipitation.

Differences in grain prices during different climate change phases were compared. For the original series, the mean grain prices were calculated and compared in each phase. For the detrended grain prices, the variability (standard deviation) and anomaly magnitude, and other statistical indexes, were calculated in each phase.

The continuous wavelet transform method (Torrence and Compo, 1998; Wu and Wu, 2005) was used to examine and compare the periodicities of precipitation and detrended grain price during different climate change phases.

2.4.2 Phased correlations between climate and grain price

The impact of climate change on food prices essentially results from the impact on grain yield per unit area. There was a significant correlation between the annual growing season (from autumn to spring) precipitation and wheat harvest in North China (Gong et al., 1983; Hao et al., 2003). In addition, the grain price of a year was also affected by the harvest of the previous year because the balance of grain storage and consumption in the previous year could be transferred to that year as well. Thus, the correlation coefficients between the detrended grain price and the precipitation in the same year and previous year, and the average precipitation of these 2 years, were calculated. The resonant periodicities of precipitation and grain price were calculated using the cross-wavelet transform method (Torrence and Compo, 1998; Sun et al., 2009; Wang et al., 2016).

Table 1 Phased changes of winter-half-year temperatures in North China, annual precipitations in Shijiazhuang, and wheat prices in Baoding Prefecture during 1736–1850[a)]

Phase		1736–1780	1781–1810	1811–1840		1840–1850
				1811–1820	1821–1840	
Temperature	Mean (°C)	−0.31	−0.60	−0.77		−0.48
	Minimum (°C)	−0.47	−1.23	–1.22		−0.54
	5-year intervals lower than the average of 1736–1850 (percentage)	0	2(33.3%)	5(83.3%)		1(50%)
	Standard deviation (°C)	0.14	0.31	0.33		/
Precipitation	Mean (mm)	631.9	657.9	568.3		553.1
	Minimum (mm)	357.1	305.7	427.3		418.5
	Years less than the average of 1736–1850 (percentage)	19(42.2%)	14(46.7%)	22(73.3%)		9(90%)
	Standard deviation (mm)	108.4	204.1	90.2		55.8
Wheat price	Mean (original) (Taels/Dan)	1.80	2.23	3.66	2.59	2.28
	Maximum (original) (Taels/Dan)	2.62	3.23	5.10	2.90	2.38
	Mean (detrended) (Taels/Dan)	−0.04	0.09	1.36	0.16	–0.27
	Maximum (detrended) (Taels/Dan)	0.77	0.97	2.81	0.48	–0.27
	Standard deviation (detrended) (Taels/Dan)	0.27	0.40	0.63	0.23	0.12

a) Date from Yan et al. (2012) and Ge et al. (2005)

The phased change of correlation between precipitation and grain price was analyzed by comparing the differences of the correlation coefficients and the resonant periodicities in different stages of climate change.

3. Results and analysis

3.1 Climate differences before and after the transition

The period 1781–1810 was the transition phase based on the winter-half-year temperature change in the NCP. Overall, the climatic transition was indicated by cooling accompanied by extreme and continually decreasing precipitation in the NCP.

The climatic transition emerged during 1781–1810, when the climate changed from a relatively warm phase of the Little Ice Age during the 18th century to the cold phase during the 19th century. The transition was indicated by a cooling trend and enlarged temperature variability. The average temperature during the cold phase (1811–1840) was 0.46°C lower than that during the warm phase (1736–1780), and the difference reached a significant level of 0.01. The standard deviation of temperatures during 1781–1810 was 221% of that in 1736–1780, but similar to that in 1811–1840 (Table 1, Figure 2a).

As shown in the annual precipitation series of Shijiazhuang (Ge et al., 2005), the climatic transition was also indicated by a shift from a relative wet phase during the 18th century to the dry phase during the 19th century (Table 1, Figure 2b). Average annual precipitation during 1811–1840 was 63.6 mm less than that during 1736–1780, and the difference reached a significance level of 0.05. The years of negative precipitation anomaly during 1811–1840 was 73.3%, in contrast to 42.2% in 1736–1780. Precipitation variability during the transition in 1781–1810 was significantly higher than that in previous and later phases (Figure 2b). The standard deviation of precipitation in 1781–1810 was 188% of that in 1736–1780 and 226% of that in 1811–1840, and the differences reached a significance level of 0.001.

As shown by the continuous wavelet of the precipitation in Shijiazhuang, the periodicity of 16–24 years was strengthened after 1780, and the periodicities of 4–6 years and 2 years were also conspicuous during 1777–1806 (Figure 3a).

3.2 Correspondence between grain price change and climatic transition

3.2.1 Phases of the original grain price change

The annual grain price in Baoding Prefecture generally increased with a trend of 0.0081 Taels/Dan per year during 1736–1850 (Figure 2c). In correspondence with the climatic transition, the average grain price was 2.23 Taels/Dan in 1781–1810. It was 0.43 Taels/Dan (23.9%) higher than that in 1736–1780, with a difference reaching a significance level of 0.001. The price further increased to 3.30 Taels/Dan during 1811–1840, with the maximum price of 5.10 Taels/Dan in 1814. Even excluding the extreme high price peak during 1811–1820, the average grain price still reached 2.59 Taels/Dan during 1821–1840, which was 0.79 Taels/Dan (43.9%) higher than that in 1736–1780.

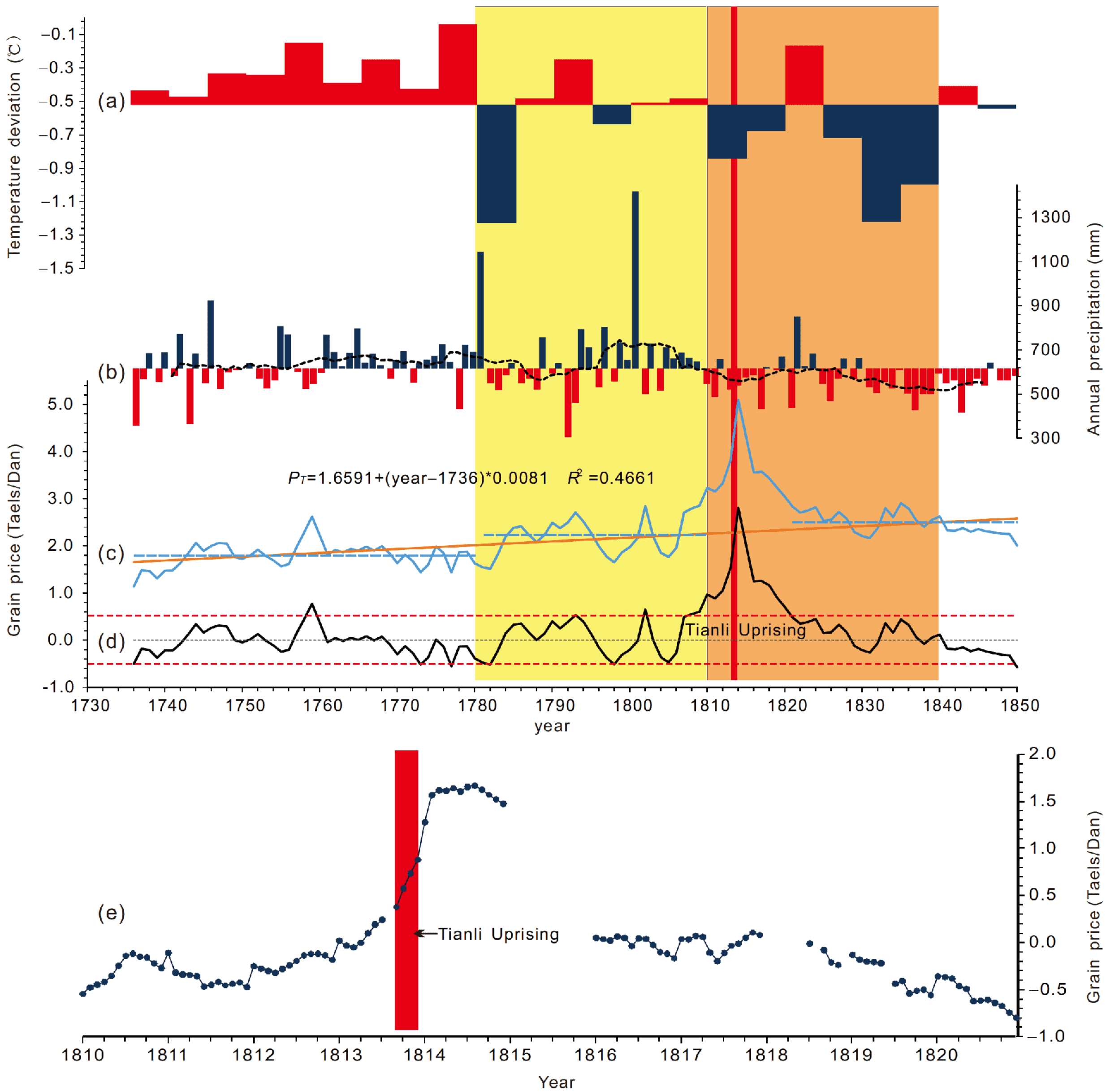

Figure 2 Climate change and grain price volatility in the North China Plain during 1736–1850. (a) Winter-half-year temperature deviation (5-year) (Yan et al., 2012); (b) annual and 10-year moving mean precipitation of Shijiazhuang (Ge et al., 2005); (c) wheat prices in Baoding Prefecture (P_T: linear trend in wheat prices); (d) detrended wheat prices in Baoding Prefecture (dashed red lines: 1 standard deviation); (e) monthly anomalies of detrended wheat prices in Baoding Prefecture in 1810–1820; light yellow shade: Climatic transition phase; light orange shade: Cold phase.

3.2.2 Phased variability and extreme magnitude of the detrended grain price

Variability of detrended grain price showed obvious phase changes corresponding to the climatic transition (Table 1, Figure 2d). The standard deviation of the detrended grain prices was 0.27 Taels/Dan during 1736–1780, with a maximum anomaly of 0.77 Taels/Dan. During 1781–1810, those numbers respectively increased to 0.40 and 0.97 Taels/Dan. There was an abnormal spike in the detrended grain price during 1811–1820 (Figure 2d), when the standard deviation further increased to 0.63 Taels/Dan. The average annual increase of the grain price reached 0.46 Taels/Dan from 1810 to 1814. The maximum anomaly was 2.81 Taels/Dan in 1814, which was 1.32 and 1.56 Taels/Dan higher than those in 1813 and 1816, respectively. The average annual decrease of the grain price was 0.35 Taels/Dan during 1814–1820. Variability of the detrended grain price during 1821–1850 receded to a level similar to that during 1736–1780.

3.2.3 Periodicities of the detrended grain price in different phases

Corresponding to the change in climatic periodicities, the periodic oscillation of the detrended grain price increased during 1781–1810. The significance of the periodicity of

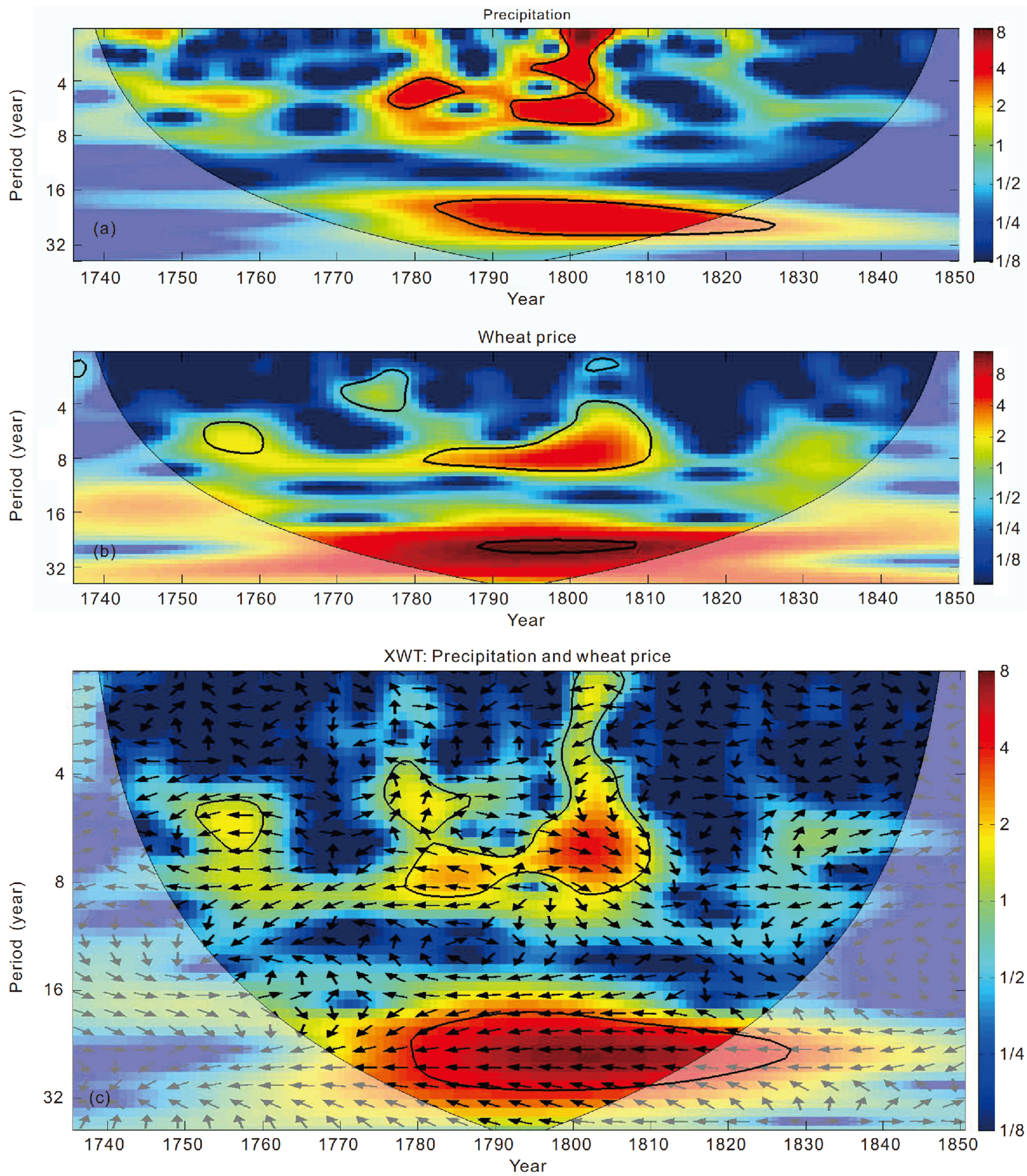

Figure 3 Continuous and cross wavelet transform power spectra of precipitation in Shijiazhuang and detrended grain prices in Baoding Prefecture during 1736–1850. (a) Continuous wavelet transform power spectra of precipitation; (b) continuous wavelet transform power spectra of detrended grain prices; (c) cross-wavelet transform power spectra of precipitation and detrended grain prices. Bold black line: critical value line of the significant periodicities (α=0.05).

18–26 years remarkably increased during 1788–1808. The significant periodicity of 6–8 years clearly emerged during 1781–1810 (Figure 3b).

3.3 Change in correlations between the grain price and precipitation before and after the climatic transition

3.3.1 Change in the correlation coefficients

From a perspective of food security, climate change could be linked to grain price through the pathway of "precipitation-grain production-grain price volatility" in the NCP. There was a significant correlation between annual precipitation in the growing season (from autumn to spring) and wheat harvest in the NCP (Gong et al., 1983). Besides the grain yield, grain price was also affected by population, consumption level, capacity of grain market regulation and other social and economic factors (Wang and Huang, 1999; Peng, 2006; Ge, 2011). The relationship between climate change and grain price was therefore more complicated than a simple causality.

There was an obvious phased change in the correlation between precipitation and grain price during 1736–1850 (Table 2). The insignificant correlation coefficients indicated that correlation was weak during 1736–1780, and there was significant negative correlation during 1781–1820. Although the variance contribution of precipitation to the grain price was insufficiently large, the remarkable increase of correlation coefficients means that the sensitivity of the grain price to precipitation fluctuation increased. There were much higher grain prices in the drought years, indicating greater variability of grain price in response to the increased precipitation variability. During 1821–1840, the correlation between precipitation and the grain prices was again weak with insignificant positive correlation coefficients (Table 2).

3.3.2 Resonant periodicities

The resonant periodicities showed the significantly intensified effect of deficient precipitation on the grain price during 1780–1810 (Figure 3c). The resonant periodicity of 18–26 years with a stable negative phase distributed continuously during 1780–1820. The periodicities of 4–6 years and 2 years with negative phase tended to be more apparent during 1780–1820.

4. Discussions: natural and socioeconomic background of grain price extremes

4.1 Change in grain price extremes

The annual grain prices higher than one standard deviation (0.52 Taels/Dan) in the detrended series were identified as extremes. A total of 16 grain price extreme years were identified, of which the distributions in both frequency and magnitude were uneven in the three phases (Table 3).

During 1736–1780, the price in 1759 was 0.25 Taels/Dan higher than one standard deviation, and this was the only year (2.22% of the period) with a grain price extreme. There were 5 years (16.7%) of grain price extremes during 1781–1810 and 10 years (100%) during 1811–1820, respectively. The increase of grain price extremes indicated the aggravated risk of food supply security. The magnitudes of the grain price extremes were remarkably high during 1811–1820. The grain prices in 7 of the 10 years were more than two standard deviation (1.04 Taels/Dan), and the maximum was more than five standard deviation. There were no grain price extremes during 1821–1850.

4.2 Correspondence between grain price extremes and drought events

The correspondence between grain price extremes and drought events varied from phase to phase (Figure 2, Table 3). During 1736–1780, there were no grain price extremes apart from 1759, although the prices were higher in the years with a negative precipitation anomaly. During 1781–1810, there was a clear correspondence between the grain price extremes and the drought events. 4 of the 5 extremes in 1793 and 1808–1810, were related to the strong negative precipitation anomalies in 1792–1793, and 1810 (Figure 2, Table 3), and the large-scale drought in 1807, which was not represented by the precipitation anomaly (Figure 2, Table 3) but recorded in the historical documents (Zhang, 2004; Tan, 2013; IGSNRR(CAS), 2016). The other extreme in 1802 was related to both extreme flood in 1801 and drought in 1802. During 1811–1820, when the climate was cold and dry, the grain production was seriously endangered by extreme

Table 2 Phased correlation coefficients between precipitation and detrended grain price during 1736–1850[a)]

Phases	1736–1780	1781–1820	1821–1840	1736–1850
Precipitation-grain price in same year	−0.056	−0.300*	0.146	−0.154*
Precipitation of the previous year-grain price	−0.100	−0.210	0.012	−0.104
Average precipitation of the year and previous year-grain price	−0.196	−0.377**	0.192	−0.202**

a) significantly correlated: ** (p<0.05; bilaterally); * (p<0.10; bilaterally)

Table 3 Correspondence between grain price extremes and winter-half-year temperature anomalies and precipitation anomalies in Baoding Prefecture during 1736–1850

Wheat price extreme (higher than 0.52 Taels/Dan)		Temperature anomaly (referencing period: 1951–1980)		Precipitation anomaly (referencing period: 1736–1850)	
Years	Price (Taels/Dan)	Interval	(°C)	Years	Percentages
1759	0.77	1756–1760	−0.15	1758, 1759	−15.0%, −10.9%
1793	0.53	1791–1795	−0.25	1792, 1793	−50.3%, −24.9%
1802	0.65	1801–1805	−0.51	1801, 1802	130.8%, −18.4%
1808–1810	0.55, 0.60, 0.97	1806–1810	−0.48	1810	−10.7%
1811–1815	0.88, 1.05, 1.53, 2.81, 2.03	1811–1815	−0.84	1811, 1813, 1814	−20.6%, −15.3%, −12.6%
1816–1820	1.25, 1.26, 1.16, 0.91, 0.71	1816–1820	−0.67	1817	−29.6%

drought events in 1811, 1813, 1814 and 1817 (Zhang, 2004; Tan, 2013; IGSNRR(CAS), 2016), along with other adverse climatic factors such as the cold climate. These extreme drought events resulted in successively poor wheat harvests in Baoding Prefecture from 1813 to 1819 (Li, 2016). These bad harvests further led to a conspicuous grain price spike (Figure 2, Table 3).

4.3 Role of socioeconomic factors in amplifying grain price extremes

There were successive grain price extremes during 1811–1820. The maximum one, in 1814, exceeded five times the standard deviation. Such successive extremes indicate that the grain market in Baoding Prefecture was seriously disturbed during this period. It is difficult to be simply explained via the impact and response chain of "climate-grain production-grain price", even considering the cold and dry climate and frequent extreme drought events during 1811–1820.

Food security in the NCP had already been in a critical state in the start of the 19th century because of continuous population growth, saturated land reclamation, sharp decreases in national silver and grain reserves, and conspicuous reduction in relief food distribution (Guo, 1995; Li and Jiang, 2008; Fang et al., 2013; Shi, 2014; Huang et al., 2014). The food security crisis was aggravated because the continuous cold and dry climate and several extreme drought events led to a large reduction in grain yield in the NCP after 1810 (Li, 2016; Fang et al., 2013). The society and economy, from a food security standpoint, were therefore highly sensitive to the impact of cold climate and extreme climatic events.

The severe food crisis during 1811–1820 not only led to the grain price spike but also a population crisis. There were 9 famine years during 1811–1820, and there were 12, 17 and 9 counties were recorded suffering from famine in 1812, 1813, and 1817, according to local gazetteers (Zhang, 2004). Moreover, there were plagues in 1814, 1815 and 1821. Notably, the large-scale plague in 1821 involved 60 counties in Zhili Province, and resulted in widespread deaths (Zhang, 2004). The subsistence crisis led to a significant increase in displaced refugees, and increased frequency and severity of revolts. Banditry incidents related to armed groups of displaced refugees increased up to 24 times during the 1810s, accounting for 64.9% of such activity during 1780–1819. The most serious incident was the Tianli Uprising in September–December, 1813. This was the first large-scale peasant uprising in the NCP during the Qing Dynasty (Fang et al., 2013; Li, 2016).

The Tianli Uprising affected the main wheat production regions in southern Zhili Province, and further exacerbated the rising grain price, as it seriously damaged agricultural production and social order. The grain price in Baoding Prefecture began to sharply increase from September 1813, when the uprising broke out, and the increase stopped in March 1814, then maintained the peak in August 1814, even the uprising was already suppressed in December 1813 (Figure 2d, 2e).

The grain market gradually returned to normal state after the uprising. The wheat price in Baoding Prefecture began to gradually decrease after August 1814. In 1816, it fell to the pre-uprising level, following a good harvest in Zhili Province in 1815 (Figure 2e).

In sum, climate change may have also strongly impacted grain prices in the NCP through the pathway of "precipitation-grain production-grain price-famine-uprising-grain price". This parallels the pathway of "precipitation-grain production-grain price".

4.4 Possible influence of demographic factors on the absence of extreme high grain prices during 1821–1850

After 1821, the average grain price in Baoding Prefecture further increased along with the cold and dry climate in the NCP. However, variation in the detrended grain price tended to be smaller, and there were no grain price extremes (Figure 2). Population decline was one of the most important potential factors for the grain price volatility. The population of Zhili Province decreased by more than 27% during 1812–1820 (Jiang, 1993), because of mass deaths caused by famine and epidemic disease (Zhang, 2004), in addition to the outward migration (Ye et al., 2012).

It is estimated that a 1°C temperature decrease could have resulted in an average grain yield decrease of 10% in the latter part of the 20th century (Zhang, 1982). The temperature during 1811–1840 was 0.46°C lower than that during 1736–1780, which could have led to an approximately 5% yield reduction in North China. The rate was significantly lower than that of population decline in North China. Such a yield reduction due to the cooling phase, relative to a 27% or more decrease of population, indicates the per capita grain supply could have increased in Baoding Prefecture during 1821–1850 (Li, 2016). In other words, the population decline could have helped alleviate the food security risk and reduce the grain price's sensitivity to climate change.

Additionally, the new crops such as corn and sweet potato, rapidly expanded in the NCP after the Reign of Jiaqing (Li, 1993). These crops were characterized by high yield, drought tolerance and barren tolerance (Cao, 2003). This may have also contributed to the relatively stable grain price after 1821 by improving the grain production's adaptability to drought and flood.

5. Conclusions

This study analyzed correspondence between the rising grain prices and climatic transition in the NCP during 1736–1850. It also explored the roles that extreme drought events and socioeconomic factors played in the grain price spike during 1811–1820. These findings could provide a historical case for better understanding the process and mechanism of climate change's impact from the perspective of grain prices. The main findings were as follows.

(1) A climate transition occurred during 1781–1810 in the NCP. There was a warm phase (1736–1780) before the transitional phase, and a cold phase (1811–1840) followed. During the transitional phase of 1781–1810, the mean temperature decreased significantly, and the variability in temperature and precipitation expanded significantly. After the transitional phase, the temperature and precipitation further decreased remarkably, and the proportion of the years with negative precipitation anomaly increased significantly.

(2) Climate change had a remarkable impact on the rise and anomaly of grain price in the NCP, indicated by significant phase correspondence between the grain price extremes and climatic transition. For the original grain price, prices became increasingly higher in correspondence with the three phases of climate change from the warm 1736–1780 shifting to the cold 1811–1840. For the detrended grain price, the variance and anomaly amplitude increased significantly during 1781–1810, and underwent a grain price spike during 1811–1820. There was a significant negative correlation between precipitation and grain price during 1781–1820. Moreover, the two series showed remarkable periodic resonance, with a negative phase during 1781–1820.

(3) The correspondence between grain price extremes and drought events was in phases. During 1736–1780, there was only one price extreme, in 1759. During 1811–1820, there were 7 extreme drought years, and 10 years with grain price extremes. The extreme drought events resulted in successive poor wheat harvests in Baoding Prefecture from 1813 to 1819, which directly led to the striking grain price spike.

(4) Socioeconomic factors also played an important role in the grain price spike during 1811–1820. Against the backdrop of enhanced sensitivity of society and economy to extreme climatic events, the Tianli Uprising in 1813 exacerbated the grain price spike. In parallel with the pathway of "precipitation-grain production-grain price", climate change could have a pronounced impact on grain price through the pathway of "precipitation-grain production-grain price-famine-uprising-grain price".

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